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from: D. P. Woodard

subject: Revised Skylab Airlock Module Coolant Loop - Calculation of Coolant Flow Division - Case 620

ABSTRACT

An analysis is given of the revised Skylab Airlock Module coolant loop (Concept 6-C) designed to provide supplemental battery cooling and to maintain a nominal 47°F coolant inlet temperature to the Airlock Module condensing heat exchangers. Inequalities are derived in terms of coolant temperatures (radiator-capacitor outlet, C&D panel outlet, and radiator inlet temperatures) to determine if the three independent vernatherm coolant control valves can maintain their respective set point temperatures. Three operational modes are considered: Non-EVA, $Q_{suit}=0$; Positive EVA, $Q_{suit}>0$; and Negative-EVA, $Q_{suit}<0$.

The analysis is incorporated into a subroutine-coded program which will find use in the Skylab atmospheric thermal model. A subroutine flow diagram and some parametric results are included.

(NASA-CR-121547) REVISED SKYLAB AIRLOCK MODULE COOLANT LOOP CALCULATION OF COOLANT FLOW DIVISION, CASE 620 (Bellcomm, Inc.) 13 p

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Conceivably other combinations might also occur.

In order to update the simplified Skylab Cluster atmospheric-fluid loop model described in an earlier memorandum[2], and to permit its use with the revised coolant loop, a computer subroutine has been written which proportions the total coolant pump flow through the three control valves and the several loop branches. In addition to the three desired set point temperatures, other key input variables are:

(1) T_1, radiator inlet temperature

(2) T_2, radiator-capacitor outlet temperature

(3) T_4, C&D panel outlet temperature

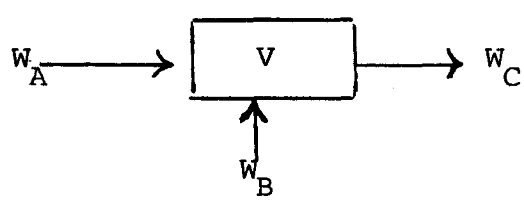
(4) Q_{suit}, EVA heat load (may be zero, positive or negative), BTU/Hr

(5) W_1, total pump flow, lbm/hr.

Several assumptions have been made in the analysis which follows. Since the fluid-to-fluid heat transfer characteristics of the Battery/Suit Cooling Module are unknown, heat transfer in this module is assumed to occur without loss from one fluid path to another. The control valves are assumed to function as follows: if possible, a valve will mix its two inputs to maintain the desired output set point temperature; if the desired set point temperature cannot be maintained, one port will open fully and the other will close so that the output fluid is as close to the desired temperature as possible. A constant fluid specific heat is also assumed.

Analysis

The analysis is based on the schematic, Figure 2, which shows the coolant mass flow rates and temperatures to be determined. For convenience, we first define a temperature valve position by the following sketch and flow ratios:



[2] "Thermal Control Capability for Crew Comfort in the Skylab Orbital Workshop", Memorandum for File, D. P. Woodard, March 24, 1971.

$$(1) \quad V = \frac{W_A}{W_C}, \qquad (2) \quad (1-V) = \frac{W_B}{W_C}, \qquad 0 \le V \le 1.$$

Using a constant coolant specific heat, energy balances at the three control valves V1, V2, and V3 are, respectively:

$$(3) \quad T_4 W_{41} - Q_3/C_p + T_4 (W_1 - W_{41}) = T_5 W_1$$

$$(4) \quad T_2 W_3 + Q_3/C_p + T_1 W_4 = T_6 W_6$$

$$(5) \quad T_2 W_5 + T_6 W_6 + Q_{suit}/C_p = T_7 W_1$$

Q_3 is the supplemental heat removed from the coolant entering the battery cold plates at the regenerative heat exchanger and transferred to the flow, W_3. Q_{suit} is the EVA heat load, which may be positive, negative, or zero, transferred through the Battery/Suit Cooling Module to either of the flows W_5 or W_6.

Rearrangement of (3) through (5) with the definitions (1) and (2) applied to the 47°F temperature control valves gives the following expressions for V_1 and V_2 in terms of flow rates and temperatures.

$$(6) \quad V_2 = \frac{W_4}{W_6} = \frac{W_1(T_6 - T_4 + T_5) + W_3(T_6 - T_2) - W_2 T_6}{T_1(W_1 - W_2 + W_3)}$$

$$(7) \quad V_3 = \frac{W_5}{W_1} = \frac{T_7 - T_6 - Q_{suit}/W_1 C_p}{(T_2 - T_6)}$$

We consider three cases: $Q_{suit} = 0$, Non-EVA mode; $Q_{suit} > 0$, positive EVA mode; $Q_{suit} < 0$, negative EVA mode.

Case I : Non-EVA Mode; $Q_{suit} = 0$.

With $Q_{suit} = 0$, V_3 is zero, and the total cold radiator coolant flow, $W_2 = W_3$, passes through the battery regenerative heat exchanger to remove the maximum amount of heat from the battery inlet flow. In this case, T_5, T_6, and T_7 can be maintained at their respective temperatures provided:

$$(8) \quad T_2 \leq (T_6+T_5-T_4)$$

This inequality is obtained from (6) by setting $V_2=0$ and noting that the maximum battery cooling will occur when $W_1=W_2=W_3$; i.e., when the radiator bypass flow is zero. Under the condition that (8) is valid, the subroutine computes an initial V_2 from (6) from which a new estimate of $W_2=W_3$ can be determined since W_1 is known. The new W_2 is averaged with its previous value and a new V_2 obtained. The iteration continues until V_2 converges, at which time we know the flows W_1, W_2 and W_3. Q_3 is then given by

$$(9) \quad Q_3 = (W_1\ C_p)\ (T_4-T_5) \text{ Btu/hr.}$$

When $T_2 > (T_6+T_5-T_4)$, the desired battery inlet temperature cannot be maintained. However, if $T_2<T_6$, some heat can still be transferred from the battery coolant and is given by

$$(10) \quad Q_3 = (T_6-T_2)\ W_3C_p \text{ Btu/hr.}$$

Since T_6 is maintained, T_7 is also properly controlled since $W_5=0$.

Case II: Positive EVA Mode; $Q_{suit} > 0$.

Coolant flow is controlled by V3 in this mode. The flow, $W_5=W_2-W_3$, is adjusted so that the addition of Q_{suit} results in T_3 equal to the desired set point temperature, T_7. With this condition T_6 must be maintained simultaneously. Computation proceeds in the following manner:

(a) V_3 is computed from (7), which in turn establishes the flow, (W_2-W_3).

(b) From (6), V2 will be open when the numerator is positive, i.e.,

$$(11)\ W_3 > \frac{W_1(T_4-T_5-T_6)+W_2(T_6).}{(T_6-T_2)}$$

If this inequality is satisfied with $W_1=W_2$, then all set points can be maintained. Subsequent iteration on V_2 (Equation 6), as described previously, determines the flows W_1, W_2, and W_3.

(c) If the inequality (11) is not satisfied with $W_1=W_2$, W_3 is known ($W_3=W_2-W_5$), and Q_3 is determined from (10). T_6 and T_7 will be maintained; T_5 will not.

Case III: Negative EVA Mode; $Q_{suit}<0$

In the negative EVA mode, heat is transferred from the hot fluid flow ($W_1-W_2+W_3$) to the EVA suit circuit. Consequently V_3 is set to zero, and $W_2=W_3$. V_1 operates independently to maintain T_5, so that Q_3 is given by (9). If the inequality (8) is satisfied, T_5 and T_6 can be maintained at their respective set points. V_2 is adjusted as before by iteration to obtain the radiator bypass flow, (W_1-W_2). Depending on $|Q_{suit}|$, T_7 will fall below its set point of 47 degrees.

In the event that (8) is not satisfied, V_2 and V_3 are set to zero (closed); $W_1=W_2=W_3$; Q_3 is given by (10); T_5 will exceed 40°F; and T_7 will be less than 47°F. A somewhat more satisfactory logic might be programmable in this instance if the heat transfer characteristics of the battery regenerative heat exchanger were known; i.e., T_5 could decrease to 40°F; T_6 could increase above 47°F; and T_7 might thus approach 47°F more closely.

A logic diagram is given in Figure 3 which will amplify the above discussion. Figures 4, 5, and 6 show some parametric results for the three modes, NON-EVA, POSITIVE EVA, and NEGATIVE EVA, as a function of radiator inlet temperature, T_1.

Utilization of Subroutine

The subroutine, FL6C (W1, T1, T2, T4, Qsuit, W2, W3, W4, W5, W6, V2, V3, ORGEN)[3], computes only coolant flow rates for the revised AM coolant loop. Temperatures may be obtained by calling on FL6C in a CINDA atmosphere-coolant loop thermal model, such as described in Reference 2, and using the several flow rates to establish fluid loop conductors in the conventional manner. An AM radiator model, either a thermal model or a parametric representation will also be required. The iteration schemes used to determine the respective flow rates may require some revision for extreme hot and cold conditions. However, this should be nominal. Copies of the program and results are available from the author.

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Attachments
Figures 1-6

[3] ORGEN is synonymous with Q_3 in the analysis and shown in Figure 3.

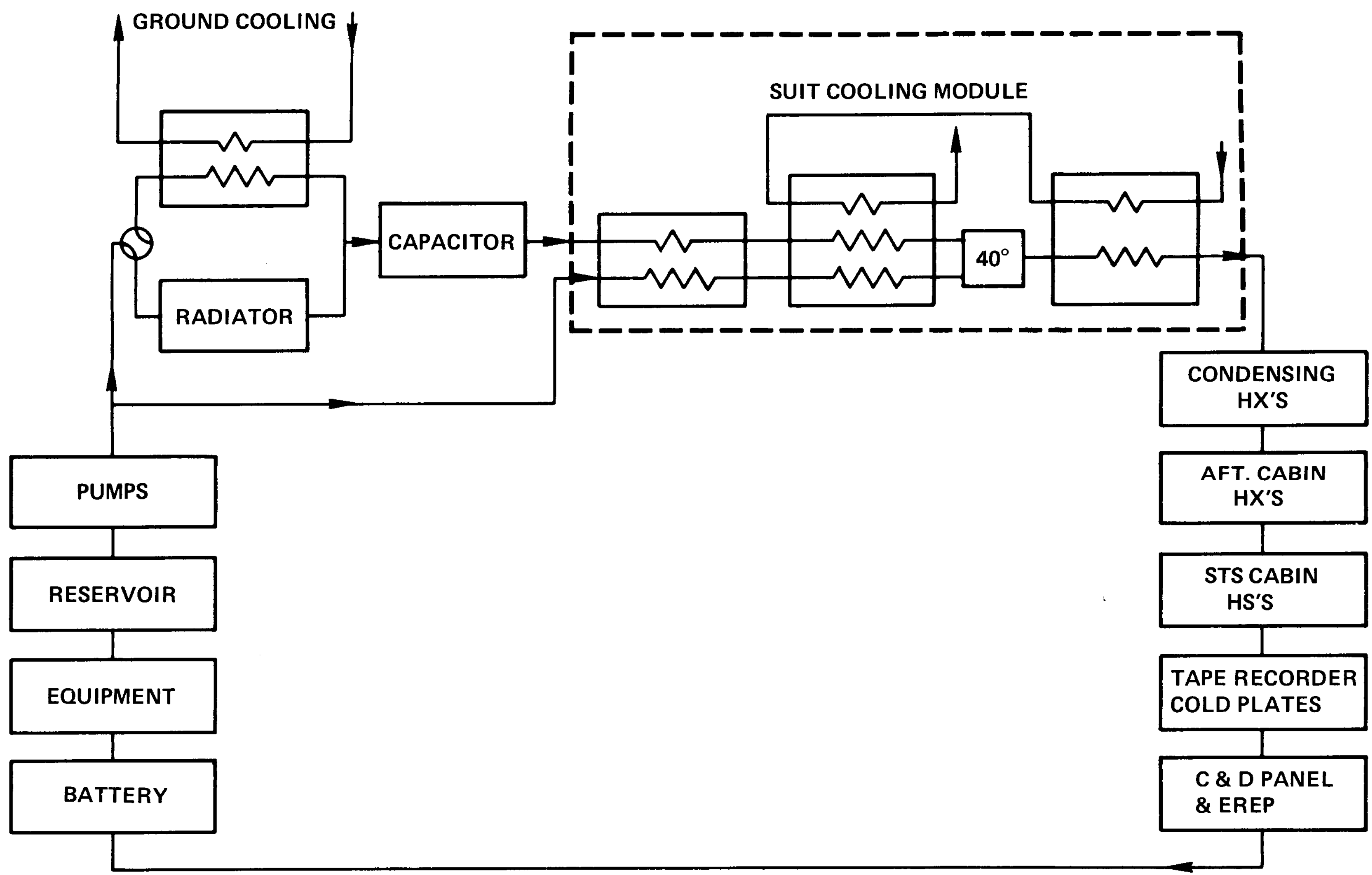

FIGURE 1 - OLD BASELINE AM COOLANT SYSTEM SCHEMATIC

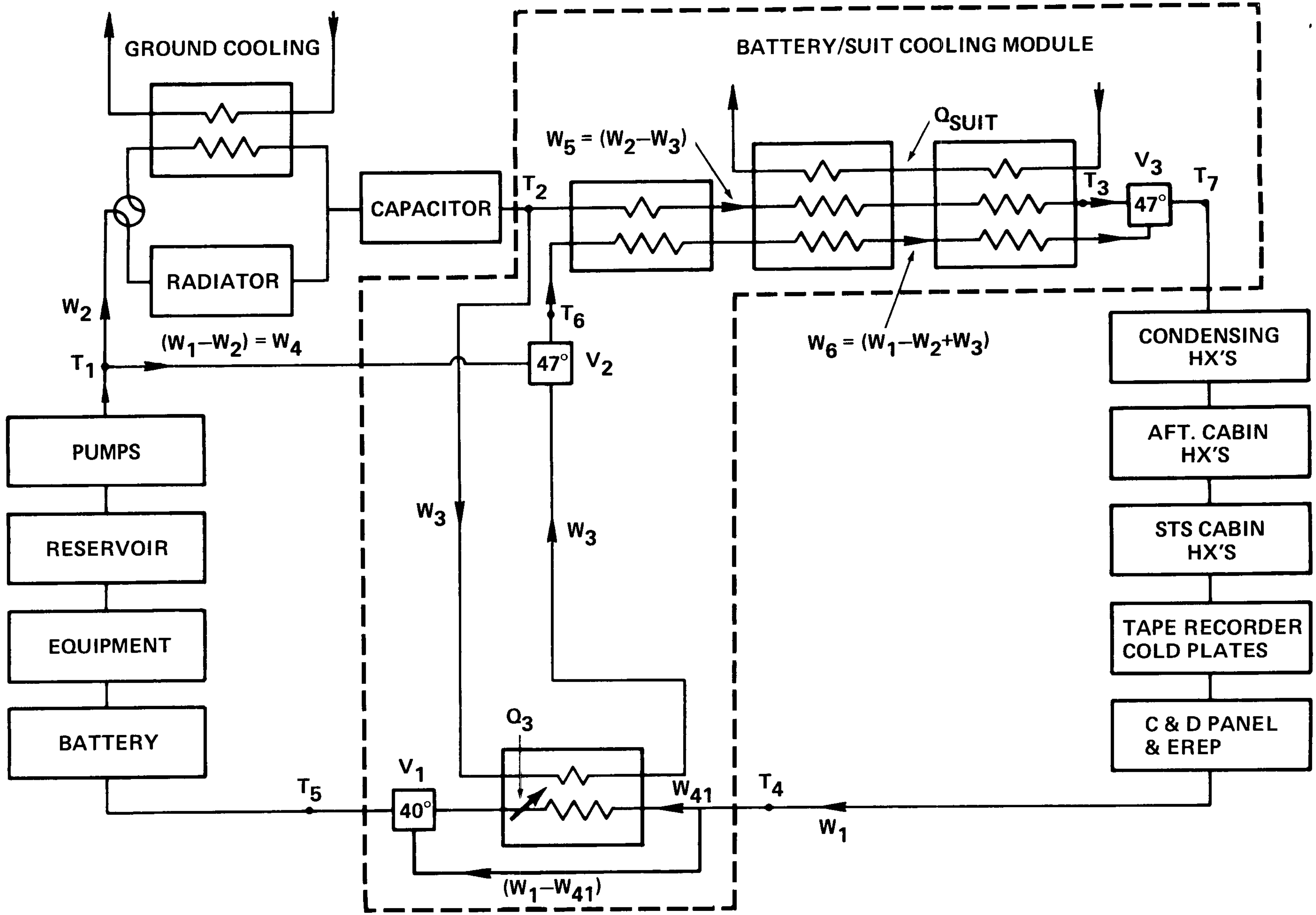

FIGURE 2 - REVISED CONCEPT 6-C AM COOLANT SYSTEM SHCEMATIC

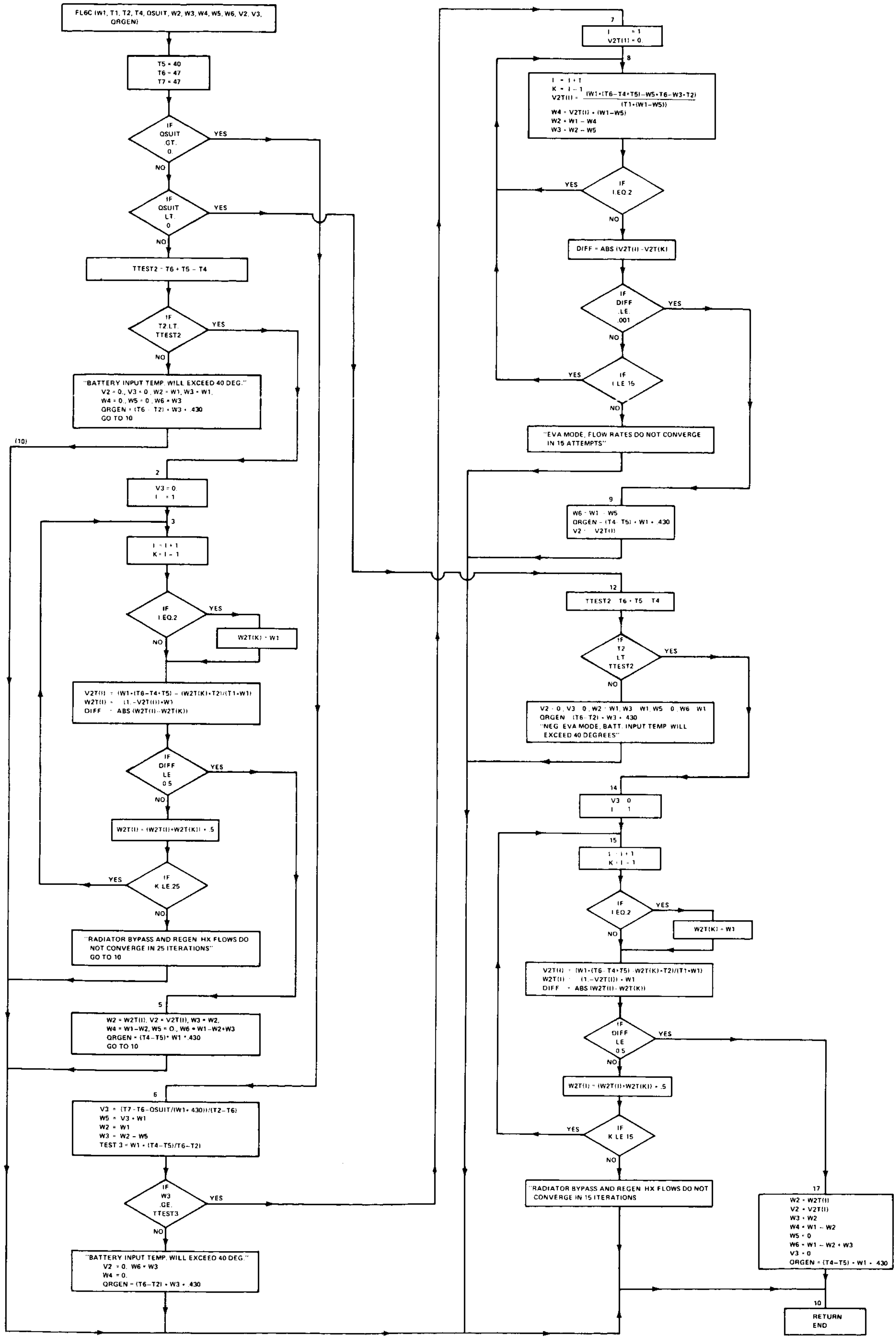
FL6C (W1, T1, T2, T4, QSUIT, W2, W3, W4, W5, W6, V2, V3, QRGEN)
T5 = 40
T6 = 47
T7 = 47
IF QSUIT GT. 0.
YES
NO
IF QSUIT LT. 0
YES
NO
TTEST2 = T6 + T5 – T4
IF T2 LT TTEST2
YES
NO
"BATTERY INPUT TEMP. WILL EXCEED 40 DEG."
V2 = 0., V3 = 0., W2 = W1, W3 = W1,
W4 = 0., W5 = 0., W6 = W3
QRGEN = (T6 – T2) * W3 * .430
GO TO 10
(10)
2
V3 = 0.
I = 1
3
I = I + 1
K = I – 1
IF I EQ.2
YES
W2T(K) = W1
NO
V2T(I) = (W1*(T6–T4+T5) – (W2T(K)*T2)/(T1+W1)
W2T(I) = (1.–V2T(I))*W1
DIFF = ABS (W2T(I)–W2T(K))
IF DIFF LE 05
YES
NO
W2T(I) = (W2T(I)+W2T(K)) * .5
IF K LE 25
YES
NO
"RADIATOR BYPASS AND REGEN. HX FLOWS DO NOT CONVERGE IN 25 ITERATIONS"
GO TO 10
5
W2 = W2T(I), V2 = V2T(I), W3 = W2,
W4 = W1–W2, W5 = O., W6 = W1–W2+W3
QRGEN = (T4–T5)* W1 *.430
GO TO 10
6
V3 = (T7–T6–QSUIT/(W1*.430))/(T2–T6)
W5 = V3 * W1
W2 = W1
W3 = W2 – W5
TEST 3 = W1 * (T4–T5)/T6–T2)
IF W3 .GE. TTEST3
YES
NO
"BATTERY INPUT TEMP. WILL EXCEED 40 DEG."
V2 = 0. W6 = W3
W4 = 0.
QRGEN = (T6–T2) * W3 * .430
7
I = 1
V2T(1) = 0.
8
I = I + 1
K = I – 1
V2T(I) = (W1*(T6–T4+T5)–W5*T6–W3*T2) / (T1+(W1–W5))
W4 = V2T(I) * (W1–W5)
W2 = W1 – W4
W3 = W2 – W5
IF I EQ.2
YES
NO
DIFF = ABS (V2T(I) –V2T(K))
IF DIFF .LE. .001
YES
NO
IF I LE 15
YES
NO
"EVA MODE, FLOW RATES DO NOT CONVERGE IN 15 ATTEMPTS"
9
W6 = W1 – W5
QRGEN = (T4–T5) * W1 * .430
V2 = V2T(I)
12
TTEST2 = T6 + T5 – T4
IF T2 LT TTEST2
YES
NO
V2 = 0., V3 = 0., W2 = W1, W3 = W1, W5 = 0., W6 = W1
QRGEN = (T6–T2) * W3 * .430
"NEG. EVA MODE, BATT. INPUT TEMP WILL EXCEED 40 DEGREES"
14
V3 = 0
I = 1
15
I = I + 1
K = I – 1
IF I EQ.2
YES
W2T(K) = W1
NO
V2T(I) = (W1*(T6–T4+T5)–W2T(K)*T2)/(T1+W1)
W2T(I) = (1.–V2T(I)) * W1
DIFF = ABS (W2T(I)–W2T(K))
IF DIFF LE 05
YES
NO
W2T(I) = (W2T(I)+W2T(K)) * .5
IF K LE 15
YES
NO
"RADIATOR BYPASS AND REGEN. HX FLOWS DO NOT CONVERGE IN 15 ITERATIONS"
17
W2 = W2T(I)
V2 = V2T(I)
W3 = W2
W4 = W1 – W2
W5 = 0
W6 = W1 – W2 + W3
V3 = 0
QRGEN = (T4–T5) * W1 * .430
10
RETURN
END

FIGURE 3

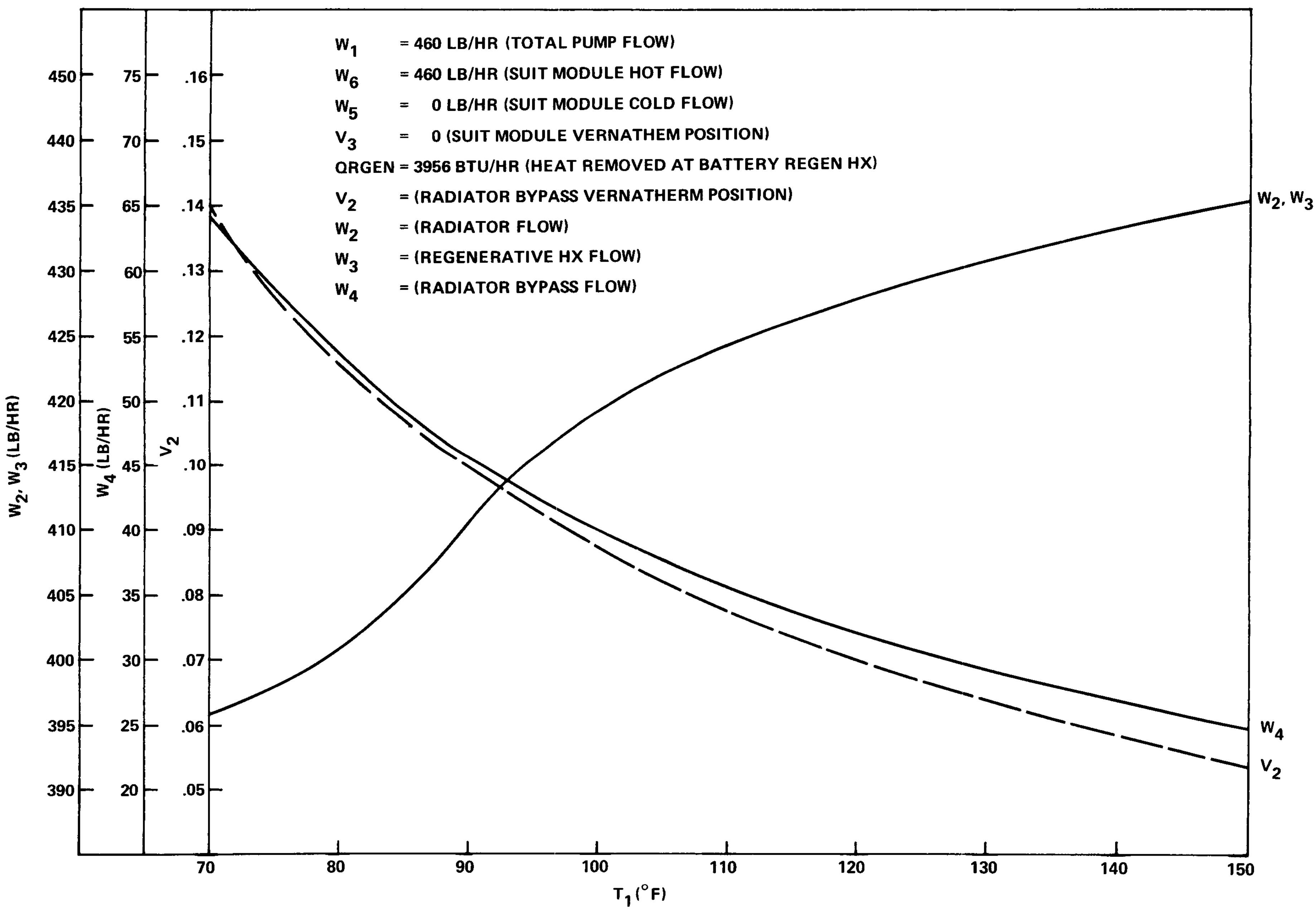

FIGURE 4 - NON-EVA MODE

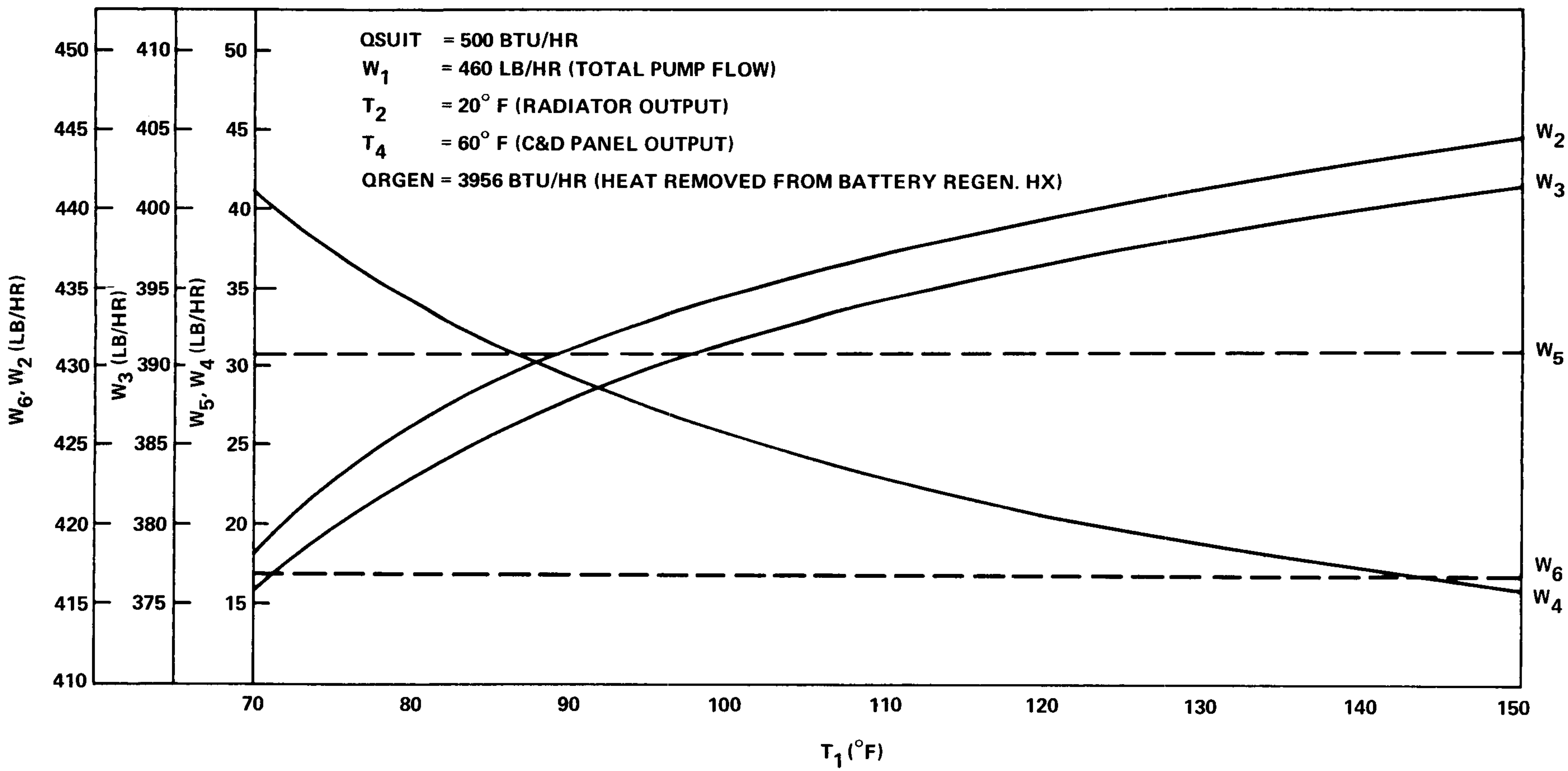

FIGURE 5 - POSITIVE EVA MODE

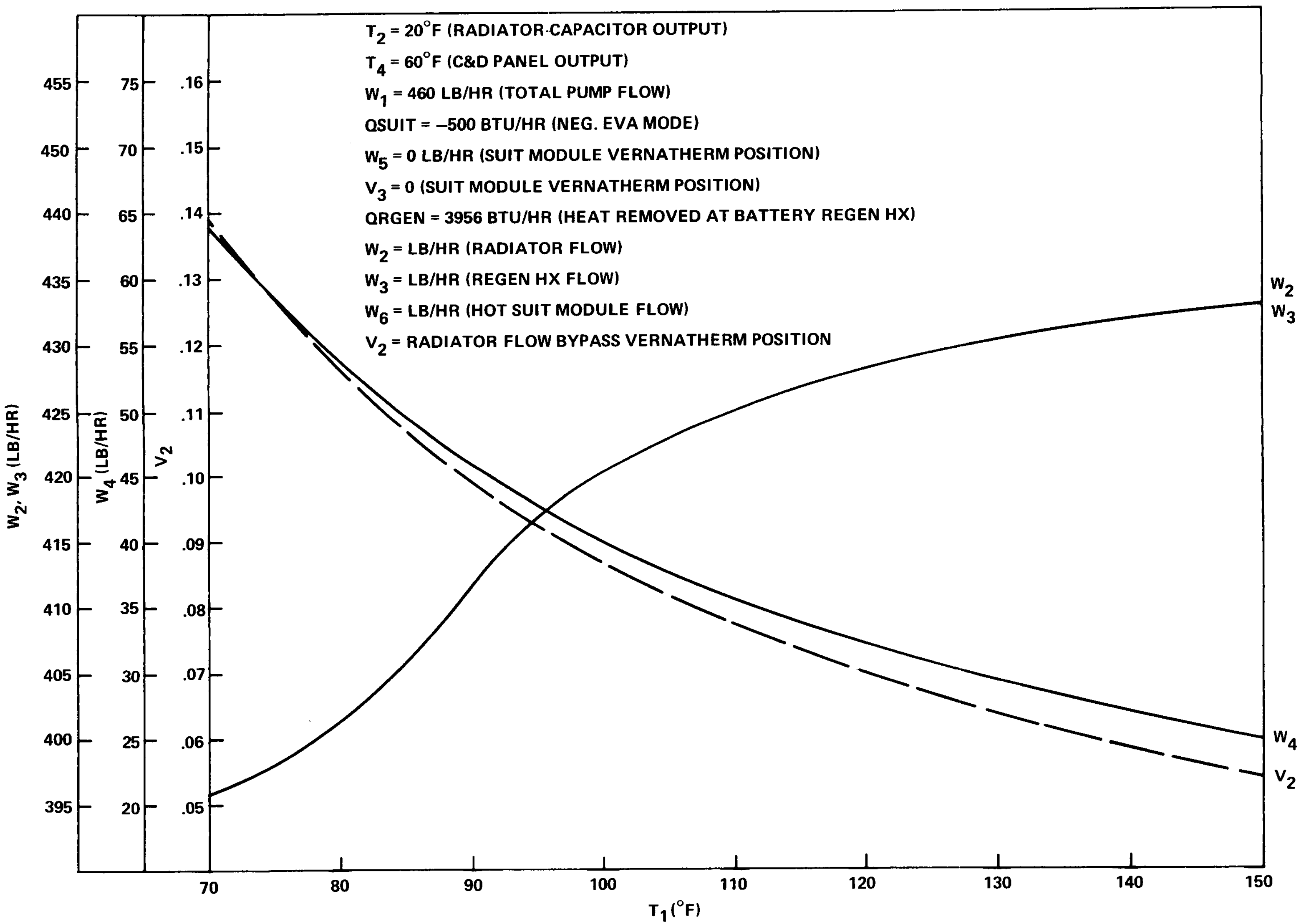

FIGURE 6 - NEGATIVE EVA MODE

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